EFFECT OF REYNOLD'S NUMBER ON DROPLET SIZE OF HOLLOW CONE NOZZLE OF ENVIRONMENT FRIENDLY UNIVERSITY BOOM SPRAYER

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This paper describes the experimentally developed relationships between Reynold's Number (Re) and droplet size of different hollow cone nozzles. The experiments were conducted at 250 kPa, 300 kPa, 350 kPa, 400 kPa, 450 kPa, and 500 kPa spray fluid pressures. The University Boom Sprayer Test Bench was employed for conducting lab experiments in the laboratories of the Department of Farm Machinery & Power and the University Boom Sprayer was employed for field experiments at the Post-graduate Agricultural Research Station experimental fields, University of Agriculture, Faisalabad. The dimensionless ratio of droplet size to nozzle aperture diameter (d/D) followed straight line trend up-to Reynold's Number 40,000, for locally made nozzle (d=1.6 mm), up-to 33,000 for imported yellow nozzle (d=1.3 mm), and upto 18,000 for imported orange nozzle (d=0.7 mm). The droplet size decreased with the increase in fluid pressure but remained constant at pressures above 450 kPa. Therefore, it would be uneconomical to spray the crop above 450 kPa due to the use of costly high pressure hoses. The critical fluid velocities for spray fluid atomization were found to be 20.36 m/s, 23 m/s, and 33.16 m/s for locally made nozzle, imported yellow nozzle, and imported orange nozzle respectively.
Key words: Reynold's Number; hollow cone nozzle; atomization;

INTRODUCTION

Due to the general complexity of many engineering problems, it is often necessary to obtain solutions through experimentations, and it is, of course, highly desirable that the experimental results be as widely applicable as possible. In this regard, with properly designed and executed experiments, results obtained on one system can be used to describe the behavior of other similar system (Young, 1995). The planning and performance of experiments on models can be greatly simplified by using dimensional analysis technique. The principal objective of the theory of dimensional analysis is to establish relationship necessary to permit reliable predictions to be made from observations on models, and to establish the type of relationship existing among the variables involved in any physical phenomenon so that the most pertinent data may be secured systematically (Murphy, 1950). Dimensional analysis and similitude are very powerful tools being employed in modeling. One fluid flow problem that does not have a satisfactory, exact analytical solution is that of flow from a hollow cone sprayer nozzle for applying insecticides in micro droplets inorder to increase plant leaves surface coverage for controlling insect pest. Therefore, the objectives of this study were to analyze fluid flow from a hollow cone sprayer nozzle and to determine the effect of Reynold's Number on droplet size.

MATERIALS AND METHODS

The experiments were conducted at 250-kPa, 300-kPa, 350-kPa, 400-kPa, 450-kPa, and 500-kPa spray fluid pressures. The University Boom Sprayer Test Bench was employed for conducting the lab experiments in the laboratories of the Department of Farm Machinery & Power and the University Boom Sprayer was employed for field experiments at the Post-graduate Agricultural Research Station experimental fields, University of Agriculture, Faisalabad.

This study consisted of development of prediction equation for droplet size, determining the velocity of fluid, measurement of droplet size and studying the effect of developed equation on droplet size.

1. Development of Prediction Equation

Droplet size was considered a function of the following variables:

$$d = f(D, V, \rho, \mu, \sigma, e) \text{ ----------------------------------- 1}$$

Where,

d = Droplet diameter, m, (L),

D = Nozzle diameter, m, (L),

ρ = Density of water, 1000 kg/m^3, (FL^{-4}T^2),

μ = Viscosity of water, 0.001 pa.s, (FTL^{-2}),

σ = Fluid surface tension, 0.0728 N/m (FL^{-1}),

e = Fluid compressibility, N/m^2 (FL^{-2}),

V = Fluid velocity through nozzle, m/s (LT^{-1})

Since there were 7-variables and 3-basic dimensions, therefore, following 4-dimensionless Pi-groups were developed using Buckingham Pi-Theorem:

$$\Pi 1 = \frac{d}{D}, \qquad \Pi 2 = \frac{\rho V d}{\mu} \quad \text{----------Reynold's Number,}$$

$$\Pi 3 = \frac{\rho V^2 d}{\sigma} \quad \text{----------------------------Weber Number,}$$

$$\Pi 4 = \frac{\rho V^2}{e} \quad \text{--------------------Effect of compressibility}$$

Therefore, Prediction equation became:

$$\frac{d}{D} = f\left[\frac{\rho V d}{\mu}, \frac{\rho V^2 d}{\sigma}, \frac{\rho V^2}{e}\right] \quad \text{------------------------ 2}$$

In chemical applications, surface tension is negligible, since chemicals are basically used to avoid surface tension phenomenon and compressibility of fluid is prominent at fluid velocity more than the speed of sound (Sheikh and Sabir, 1984). Therefore, Weber number and Mach number were not considered effective in this study. The prediction equation-2 was simplified as following:

$$\frac{d}{D} = f\left[\frac{\rho V d}{\mu}\right] \quad \text{--- 3}$$

2. Determination of velocity

As the liquid flow rate is increased by increasing the pressure, it goes through the phases of drop formation, varicose region, sinuous region and atomization based on the Reynold's number. During crop spraying atomization phase is very important. To produce the desired droplet size in atomization phase, the jet breaks down into small droplets usually within the distance of 15-times the jet diameter of the orifice. The break up is highly chaotic. The ligaments shed at the crest as the jet oscillates with further break down into droplets, and leading to atomization. Srivastava (1993) reported a formula that jet velocity (V_j) of any nozzle can be calculated with given diameter, at which atomization will occur.

$$(d_j \, V_j \, \rho_l) / \mu_l > 2.8x \, 10^2 \, [\, \mu_l / (\sigma_l \, \rho_l \, d_j)]^{1/2}\,]^{-0.82} \text{----------------- 4}$$

Rearranging, $\quad V_J > 280 \, \sigma^{0.42} \, \mu^{0.18} / \rho^{0.59} \, d_j^{0.59}$ --------------- 5

Where, V_j = Jet velocity (m / s),
ρ = Liquid density (Kg / m^3),
μ = Liquid viscosity (pa s),
σ = Surface tension (N / m),

d_j = Jet diameter (m)
Knowing nozzle flow,

$$V_j = Cv \, (2 \, \Delta p / \rho_l)^n \quad \text{-- 6}$$

Where, Cv = Velocity coefficient,
Δp = Total pressure drop (pa),
n = 0.5 for turbulent flow
Volumetric flow rate, $\quad Q = V_j \, Ca \, A$ --------------------- 7
Where, Ca = Area coefficient,
A = Nozzle surface area (m^2)
Finally, $Q = Cv \, (2 \, \Delta p / \rho_l)^{1/2} \, Ca \, A$------------------------ 8
Let, Cd = Cv Ca = Discharge coefficient
Then, $\quad Q = C_d \, A \, (2 \, \Delta p / \rho l)^{1/2} = C_d \, A \, (2gh)^{1/2}$----------- 9
or, $\quad Q = C_d \, A \, V_j$
Average jet velocity, $V_j = Q / C_d \, A$----------------------- 10
To calculate the value of C_d, graph of "Q" Vs "$\sqrt{\Delta p}$" could be drawn. The slope of line is
"$C_d \, A\sqrt{2/\rho_l}$". From the slope 'C_d' could be found easily as following:
Because, $Q = C_d \, A \, (2 \, \Delta p / \rho_l)^{1/2} = [C_d \, A \, (2 / \rho_l)^{1/2}] \, \sqrt{\Delta p}$
Therefore, slope, $\quad Q / \sqrt{\Delta p} = [C_d \, A \, (2 / \rho_l)^{1/2}]$
$C_d = (Q / \sqrt{\Delta p}) / A \, (2 / \rho_l)^{1/2}$ --------------------------------- 11
Jet diameter was measured using microscope, confirmed with the help of scanner, AutoCAD using Pentium-4 Computer and recorded in Table-1.
The spray boom was installed on the University Boom Sprayer. After setting desired pressure, nozzle discharge of each nozzle was measured in the graduated cylinder for a period of 60 seconds (1 minute) and droplet sizes were also determined. Hollow cone (HC) nozzles tested were as following:
a) HC, Punjab Engineering Co. FSD. (Local)
b) HC / 0.8 / 3.00 (International Ltd. UK) Yellow
c) HC / 0.4 / 3.00 (International Ltd. UK) Orange
Experiments were conducted at 250 kPa, 300 kPa, 350 kPa, 400 kPa, 450 kPa, and 500 kPa spray fluid pressures.

3. Determination of droplet size

Droplet size is the most important parameter of nozzle performance. An optimum droplet size is one, which gives most effective coverage of the target with minimum contamination of the environment. Due to certain operational problems, spay droplet size could not be measured directly. The droplet size was calculated from already reported formula given by Fraser (1956) for nozzle hollow cone type and for pressure from 5 psi to 200 psi using water as fluid.
$$d = 437 \, (FN / P)^{1/3} \quad \text{--- 12}$$
Where, d = Droplet size in microns (10^{-6}),
FN = Flow number = (Discharge, gal/hr)/ $\sqrt{}$(Pressure, psi), P = Pressure of fluid (Psi)

RESULTS AND DISCUSSION

i) Effect of Pressure on Droplet size

Spray droplet size is the important parameter of nozzle performance. An optimum droplet size is that, which gives most effective coverage of the target with minimum contamination of the environment. In order to determine the effect of pressure on droplet size, Equation 12 was used. From the experimental data, values of droplet size (d) were calculated for different values of pressure. Prediction equations were developed using regression analysis techniques (Steel and Torrie, 1980) and plotted in Figure 1. It was observed that the droplet size decreased with the increase in pressure but remained constant at higher values of pressure after 450 kPa. This indicates that to work at pressures greater than 450 kPa will be uneconomical since high pressure hoses will be required, which will definitely increase the cost. The functional relationships found were as following:

$d = 259–0.4909\ P+0.0005\ P^2$ $R^2 = 0.99$ (King) ------- 13
$d = 242–0.4886\ P+0.0005\ P^2$ $R^2 = 0.98$ (Yellow) ---- 14
$d = 207–0.4203\ P+0.0004\ P^2$ $R^2 = 0.99$ (Orange) ---15

Where; d = mean droplet size (μm), and p = pressure (kPa)

The predicted lines followed the same trend as observed by Sheikh and Sabir (1984). The higher R^2 values for all the three models indicated that these could be the most appropriate equations to explain the relation between droplet size and pressure. The droplet sizes for pressure range of 250 to 500 kPa (36.3 – 72.5 psi) were found within the range of 101 to 200 μm. that is usually suitable for insecticide application Rehman (1994). Because a fine spray (101–200μm) is considered best and preferred when a compromise between reduced drift and good coverage is needed. Good coverage means distribution of droplets on a particular target in such a way that target receives a large number of droplets.

ii) Effect of Reynolds number on droplet size

The relationship between the droplet size and variables like the geometry of nozzle, fluid properties and velocity of fluid was developed using dimensional analysis and Buckingham Pi theorem. Reynolds number, which contains the effects of geometry of orifice and the properties of fluid such as density, viscosity, dominates the fluid flow in sprayer applications. The dimensionless ratio of droplet size to orifice diameter was considered to be a function of Reynolds number (Equation 3). To calculate velocity (V), coefficient of discharge (C_d) was calculated using

the nozzle discharge data (Equation 10). To find C_d. Equation 11 was used. The experimental data of discharge (Q) were plotted against square root of pressure ($\sqrt{\Delta p}$) for all the selected nozzles (Figure 2). Using least square method, linear models having R^2 values 0.97, 0.97, & 0.96 for locally manufactured (King) and imported Yellow and Orange nozzles respectively were found the most appropriate.

$Q = -3x10^{-8}X + 9x10^{-7}$ $R^2 = 0.97$ Local nozzle----------------16

$Q = -2x10^{-6}X + 9x10^{-7}$ $R^2 = 0.97$ Imported Yellow nozzle---17

$Q = -1x10^{-7}X + 4x10^{-7}$ $R^2 = 0.96$ Imported orange nozzle---18

Where, Q = Discharge, m^3/s and
X = pressure, kPa, square root, ($\sqrt{\Delta p}$)
Using the Equation 11 and slope of line (Q / $\sqrt{\Delta p}$) from Figure-2, coefficient of discharge for different nozzles were calculated and recorded in the Table 1. Table 1 indicates that the decrease in diameter increases the coefficient of discharge, which proves the fact that smaller the nozzle aperture size greater the resistance to fluid flow. Knowing the nozzle flow rate (flow measured for known time) and coefficient of discharge 'C_d' for each nozzle type, the fluid velocities at different pressures. The dimensionless ratios 'd/D' and Reynold's Number 'Re' were determined and plotted in Figures 3,4, & 5. Quadratic models having high R^2 values were considered the best for predicting the experimental results. The functional relationship developed for different nozzles are given as following.

$d/D = 0.3409–1x10^{-5}\ Re+1x10^{-10}\ Re^2$
 (local HC / King) ------------------------------- 19
$d/D = 0.3305–1x10^{-5}\ Re+2x10^{-10}\ Re^2$
 (imported HC/ 0.8/ 3 Yellow) ----------------- 20
$d/D = 0.6269–5x10^{-5}\ Re+1x10^{-9}\ Re^2$
 (imported HC/ 0.4/ 3 Orange) ---------------- 21
Where,
d/D = Dimensional ratio of droplet size and nozzle aperture size, and
Re = Reynold's Number
Reynolds number is the ratio of inertial force to viscous force. A small Reynolds number means viscous forces dominate over inertial forces, and large means inertial forces are predominate. A small value of Reynolds number may arise from very large viscosity, a very small velocity and very small dimensions of nozzle aperture. It can be safely concluded from Figures 3,4, & 5 that the regressed lines followed almost straight line trend up-to Reynolds number 40,000 for locally made nozzle, up-to 33,000 for imported yellow nozzle and up to 18,000 for imported orange nozzle
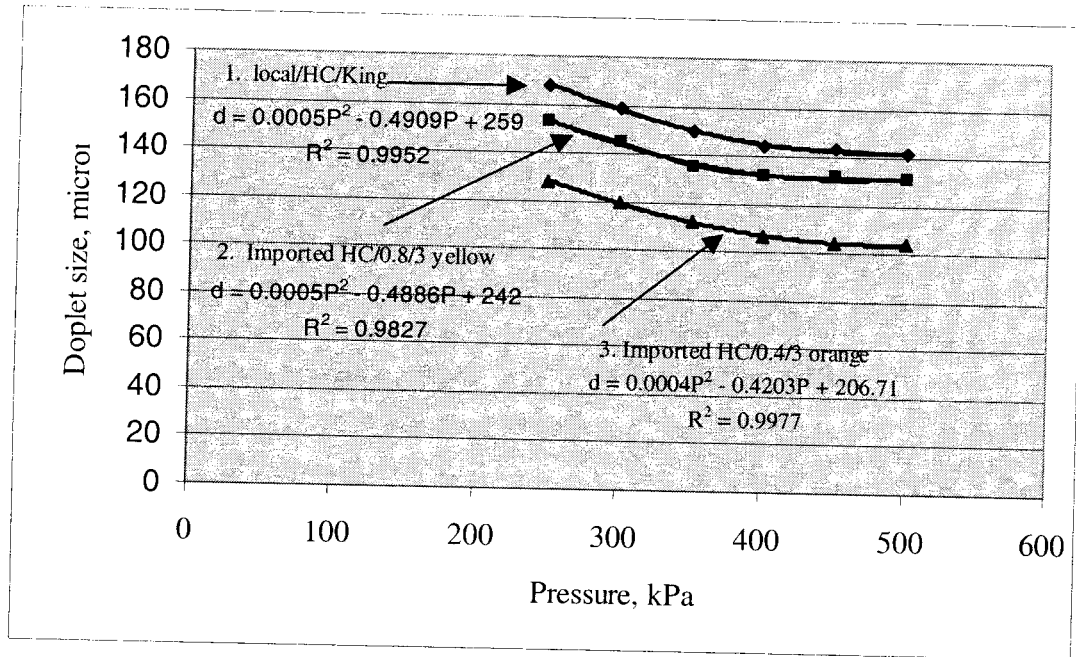
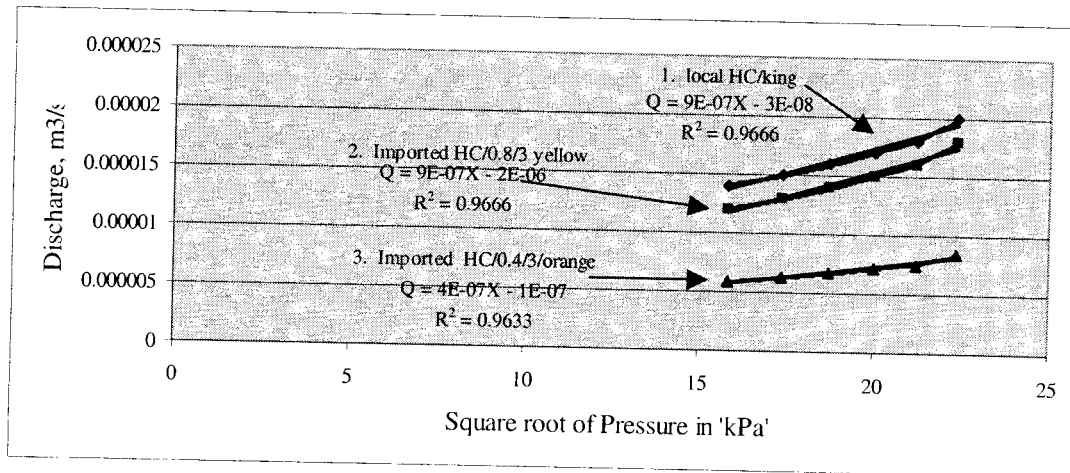Figure 1. Effect of fluid pressure on droplet size of hollow cone nozzle

Figure 2. Effect of square root of pressure on hollow cone nozzle discharge

(HC/King, dia=1.6 mm, Cd=0.35)

$$d/D = 1E{-}10Re^2 - 1E{-}05Re + 0.3409$$
$$R^2 = 0.9938$$
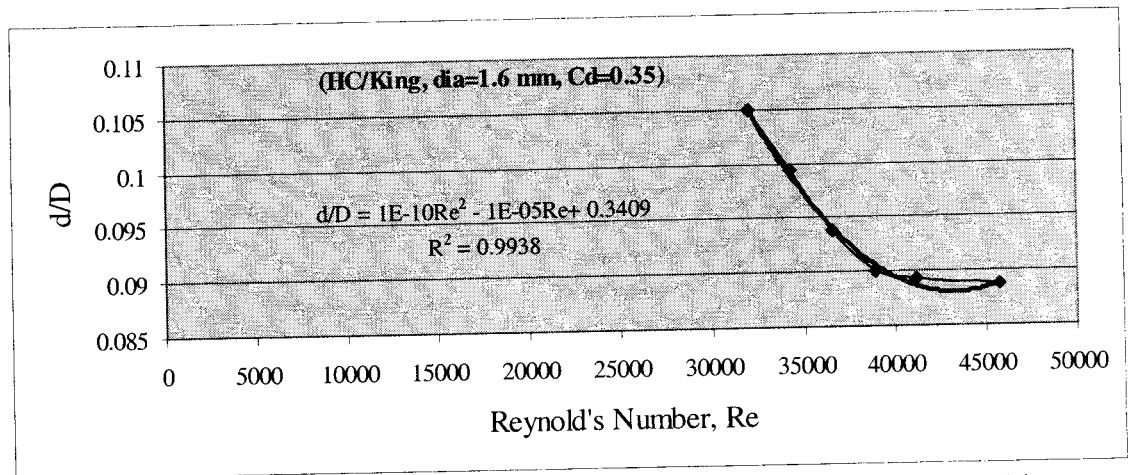
Figure 3. Effect of Reynold's Number on dimensionless ratio 'd/D' (Local HC/king nozzle)

(HC/ Yellow, dia=1.3 mm, Cd=0.48)

$$d/D = 2E{-}10Re2 - 1E{-}05Re + 0.3305$$
$$R2 = 0.9748$$
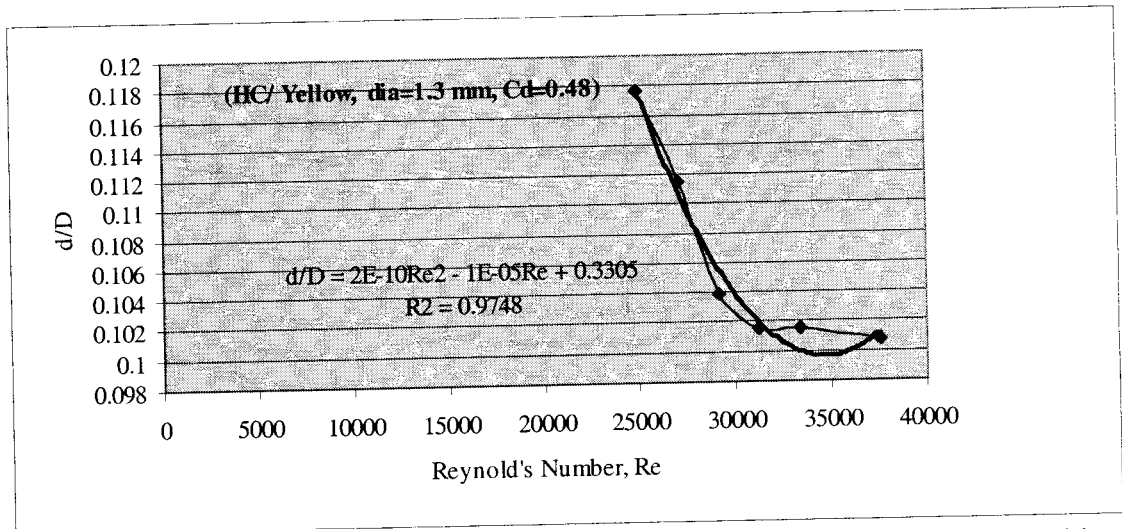
Figure 4. Effect of Reynold's Number on dimensionless ratio 'd/D' (Imported HC/0.8/3 Yellow nozzle)

(HC/orange, dia=0.7 mm, Cd=0.74)

$$d/D = 1E{-}09Re^2 - 5E{-}05Re + 0.6269$$
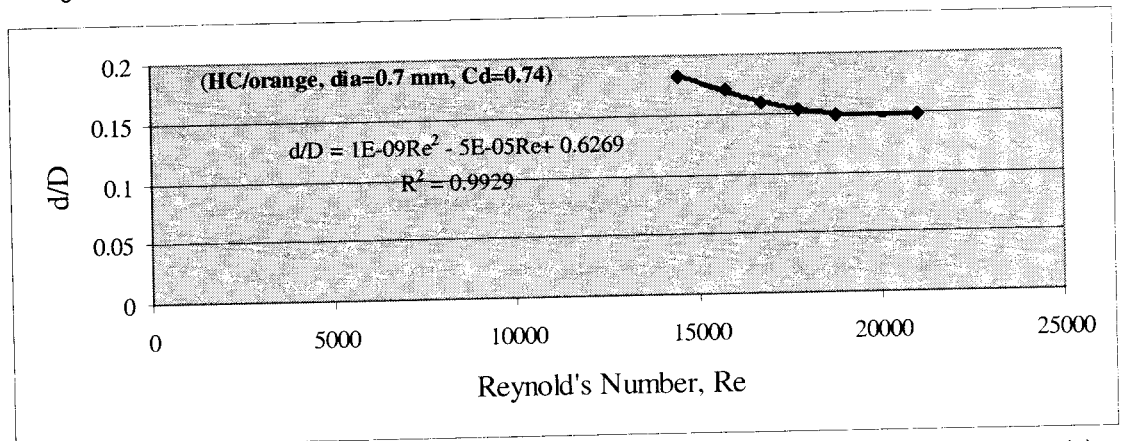$$R^2 = 0.9929$$

Figure 5. Effect of Reynold's Number on dimensionless ratio 'd/D' (Imported HC/0.4/3 Orange nozzle)

respectively. These values of 'Re' were found approximately at 450 kPa fluid pressure. These results support the above conclusion of negligible change in the drollest size after 450 kPa pressure. Therefore, it is recommended that for safe spraying operation the

M.S. Sabir. 1984. Faculty of Agricultural Engineering & Technology. University of Agriculture, Faisalabad.

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Table 1. Atomization velocity and coefficient of discharge for nozzle.

Nozzle type	Nozzle diameter (m)	Vj (m / s)	Coefficient of discharge, C_d
Local (King)	0.0016	20.36	0.35
Imported (Yellow)	0.0013	23.00	0.48
Imported (Orange)	0.0007	33.16	0.73

system should not be operated above 450 kPa fluid pressure.

iii. Velocity of fluid atomization

Velocity for atomization of fluid flow through a nozzle for each type of nozzle was calculated using Equation-5 and recorded in Table 1. The values of velocity in Table-1 are the minimum values at which liquid atomization starts for respective nozzles. The nozzle fluid pressures were developed in order to achieve the above calculated velocities for respective nozzles, in order to have atomization process be started. The above recommendations made for droplet size and Reynolds number well meet the velocity requirements for each nozzle type.

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